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The Role of "Extra-Vestibular" Inputs in Maintaining Spatial Orientation in Military Vehicles

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Summary

An individual's sense of spatial orientation is commonly attributed to be derived from visual, vestibular, and proprioceptive inputs. Spatial disorientation is often ascribed to arise from a conflict between one or all of these three systems. However, relying on this well studied view of spatial perception has not totally explained motion intolerance and spatial disorientation. It is likely that more than these three systems are involved in spatial orientation. This paper examines how cues obtained from posture, respiration, and blood flow contribute to spatial orientation. Disordered regulation of any of these factors can be identified in land based tests and allows us to study pre-disposing factors to motion sickness. In addition, examining these factors in motion environments allows us to study the mechanisms involved in motion intolerance. Postural studies were obtained in a cohort of individuals experiencing motion sickness in a variety of military environments. A definite pattern of altered postural control on land was demonstrated in over seventy percent of these individuals. The predictive value of this test and refinement of the test for increased accuracy as a pre-screening method are examined in this report. A second cohort of individuals was examined while underway in a United States Navy ship. Respiratory and postural measurements were performed on 3 motion sick and three non-motion sick individuals within 24 hours of going to sea as well as 48 hours after the first measurement. Initial postural and respiratory adaptations were compared to ship motion and the strategies of individuals without motion sickness were compared to the strategies of the motion sick individuals. Adaptive patterns were examined in each group and found to be complete within 48 hours. The implications of these findings are examined in developing strategies to deal with spatial disorientation in a number of military settings. Technology is examined that might help us to better test individuals for adaptive strategies and train them so that spatial disorientation is not an issue in a planned operational event.

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Introduction
Traditional teaching holds that balance control requires an integration of visual information (the eyes), vestibular information (the inner ears), and proprioceptive information (the hips and the ankles). These inputs are hypothesized to be integrated at the level of the brainstem for reflex control and this integrated message is interpreted at a higher cortical level. The traditional view also focuses on reflex loops such as the vestibular-ocular reflex that coordinates eye and head motion and the vestibular-spinal reflex that coordinates head on spinal cord motion. While the traditional explanation of coordinated balance explains how humans generate adaptive reflex responses to postural challenges and some aspects of orientation perception under static conditions, it does not offer a coherent explanation for phenomena such as motion sickness, mal de debarquement and motion adaptation disorders. [1,2]

The sensory conflict theory of motion sickness states that motion sickness arises when one or several inputs from the body's sensory systems are in conflict (disagree) with inputs from other sensory systems and do not match previous neural patterns.[3] With only the traditional balance system this theory does not explain why drivers of cars rarely experience motion sickness while the same individual as a passenger in the car (even in the front seat) will experience motion sickness on the exact same drive.[4] Certainly, the sensory conflicts in the traditional balance system are no difference whether you are sitting on the left or right side of the car. In addition, the traditional balance system does not explain why individuals experience simulator sickness in full motion simulators, which are designed to mimic operational flying scenarios, whereas the same individuals do not experience motion sickness when the simulator does not move as much. Certainly, the sensory conflict is greater in the lower motion simulator. Because we could not explain human spatial orientation in a motion environment based on the traditional balance system, our group began to examine "extra-vestibular" inputs into the balance system. We believe that, especially in a motion environment, a set of influence primarily generated from the trunk may be very important in humans maintaining spatial orientation. For the purposes of this discussion, the term "extra-vestibular inputs" refers to inputs from parts of the body that are not "traditionally" considered to influence balance. We will present three pieces of evidence that suggests that bodies under the influence of motion rely on inputs outside of the traditional vestibular-visual-proprioceptive system to sense position and to maintain posture and spatial orientation.

Postural Stability and Motion Sickness
At the Department of Defense Spatial Orientation Center (DSOC) we have had an ongoing trial examining a group of patients with significant chronic intractable motion sickness (CIMS). The individuals in this study must have several episodes of severe motion sickness during an operational military assignment (usually aboard ship), but demonstrate no balance disorder or ear pathology when not in a motion environment. Examining some of the vestibular testing results in this group of patients provides us one piece of evidence that supports "extra-vestibular" inputs into the balance system.

Materials and Methods
Individuals presenting to DSOC with chronic intractable motion sickness that had presented during several operational assignments were admitted into the study as were a set of control subjects selected to mirror the sex and age distribution of our patients. All of the individuals in the study underwent an extensive history and physical examination for balance function. Balance function tests included Rotational chair testing (Micromedical Inc., Chatham, Illinois) and Computerized Dynamic Posturography Testing (CDP) (Neurocom Inc., Portland OR). Rotational chair testing consisted of the following: 1) Sinusoidal harmonic acceleration .02, .08, .32 and .64 Hz at a maximum velocity of 80 degrees/sec^2, 2) Visual fixation suppression (VFX) testing at .04 Hz SHA at 60 degrees/sec^2 velocity and vestibular-visual interaction testing

(VVOR) at .04 Hz and 60 degrees/sec^2 velocity, 3) Computerized rotation chair velocity-step testing at 100 degrees/ sec^2 for clock wise rotation (CWR), clockwise stop (CWS), counter clockwise rotation (CCWR) and counter clockwise stop (CCWS) , and 4) Computerized rotation chair oculomotor function tests. CDP testing included the following tests: 1) The six Sensory Organization Subtests, 2) The Motor Control (Linear Translations) Subtest, and 3) The Adaptation Tests (Toes-up and toes-down).

Results

The motion sick group of patients consisted of 18 active duty individuals (13 males/ 5 females) The age range was 19-36 years of age with a mean age of 27 years of age. This group was compared to a control group of 18 active duty individuals (13 males/5 females) with an age range of 23-38 years of age and a mean age of 30 years of age. There was no significant difference between the demographic factors in the two groups. On functional vestibular evaluation all members of both groups reported no disequilibrium or dizziness on land. However, CDP testing was normal in all of the members of the control group, whereas 72% of the motion sick group of patients had abnormal CDR results particularly in conditions 5 and/or conditions 6.

Discussion

Our results indicate that a high percentage of individuals with motion sickness demonstrate postural control abnormalities. This is in agreement with the findings of other groups. [5,6] We believe that these postural control abnormalities are fundamental to stability in motion and are at least partially responsible for motion sickness. This argument is supported by findings from two subsets of these individuals who responded to vestibular rehabilitation therapy. One group of patients was composed of individuals who had abnormalities in the vestibulo-ocular reflex (VOR) (as measured on rotational chair testing) and who normalized their VOR function with therapy. Despite the improvements in testing, these individuals continued to experience motion sickness. The second subset of patients was those who demonstrated abnormalities on CDP testing and whose abnormalities improved with therapy. These individuals were cured of motion sickness.

Findings in our motion sickness group of patients support the fact that posture affects spatial orientation and stability particularly during motion and that those who lack postural control will have difficulty with spatial orientation in a motion environment. This difficulty with spatial orientation is expressed as motion sickness and/or anxiety.

Anatomical Findings

The realization that there are extravestibular sensors for sensing gravitoinertial acceleration is base on the recognition that all tissues in the body have mass. The implication of this truism is that gravitoinertial acceleration will impact directly on pulmonary function,[7] movements of the abdominal viscera within the peritoneal cavity [8,9](sensed by traction on mesenteries, contact with parietal surface of peritoneum and stretch due to pressure on diaphragm),[10, 11] regional blood distribution (including ‘orthostatic responses’), intraocular pressure,[12] and intracranial pressure.[13] The reader is referred to a review chapter by Balaban and Yates (in press) for a detailed discussion of each of these potential mechanisms.[4] A brief overview of biomechanical bases for these effects has been included below.

The mammalian torso is divided into an abdominal/pelvic cavity and a thoracic cavity, separated by a musculotendinous septum, the diaphragm. These cavities are surrounded by striated muscles that move the trunk (e.g., intercostal muscles, abdominal muscles, sternocleidomastoideus and scaleni) and muscles of the pectoral girdle that have the capability to change the configuration of the torso and volume of the internal cavities. The thoracic viscera are contained in a median compartment, the mediastinum (e.g., heart and esophagus), and paired lateral pleural compartments.

The abdominal contents can be divided into two component systems that are affected directly by gravitoinertial acceleration, [14] organs tethered (directly or indirectly) to the diaphragm and organs that are connected loosely to the posterior abdominal wall. [15] As verified by dissection in primates, the thoracic surface of the diaphragm is tethered by the attachment of the pericardial sac both to the central tendon of the diaphragm and the muscular part of the left dome of the diaphragm. The abdominal surface is attached firmly to the liver by the coronary ligament, the right and left triangular ligaments and the appendix fibrosa hepatis (an extension of the left triangular ligament). As a result, the mass of the liver may be viewed as a load on the diaphragm, ligaments of the liver and pericardial attachments that are sensitive to the direction of gravitoinertial acceleration. On-going studies are investigating the distribution of mechanoreceptor-like nerve endings in the regions of attachment between the diaphragm, pericardium and liver.

The abdominal viscera, on the other hand, are covered by a visceral peritoneum, which forms both a dorsal mesentery that suspends the viscera loosely from the posterior abdominal wall and a small ventral mesentery that attaches stomach and proximal duodenum to the anterior abdominal wall. This loosely tethered gastrointestinal tract can be viewed as a fluid-filled balloon that deforms when subjected to a linear acceleration. Thus, it produces a variable gravitational load on the diaphragm during attainment of various postures (supine, lateral decubitus, prone or inverted), such that the earth-down aspect of the diaphragm is loaded differentially.[14,16] These factors appear to be determinants of gravity-dependent gradients in transpulmonary pressure,[15] respiratory movements during locomotion[9] and respiratory function during water immersion[14] and microgravity conditions.[17] It seems clear that these effects of gravitoinertial acceleration may improve local visceral and somatic motor control in the face of gravitoinertial challenges during imposed and self-generated movement.

Changes in the orientation of the orthostatic column are another potential source of information regarding changes of the orientation of the long axis of the body relative to gravitoinertial acceleration. Regional changes in blood pressure and blood volume are detected by arterial baroreceptors, atrial and ventricular pressure receptors, epicardial receptors, pulmonary and renal baroreceptors and venous stretch receptors,[10] many of which respond to both steady-state blood pressure and to the rate of change (derivative) of blood pressure.[10,18]. These receptors comprise the afferent limb for orthostatic responses, which maintain mean blood pressure in the face of an orthostatic challenge. However, in a broader sense, orthostatic reflexes (feedback control of mean blood pressure) and the phenomenon of 'baroreflex resetting' preserve the sensitivity of baroreceptor afferents to rapid changes in body orientation.[19] In the same way that gamma motoneurons match the operating range of stretch receptors in muscle spindles to the length of extrafusal muscle fibers, one role of baroreflex mechanisms can be conceived as 'rezeroing' the blood distribution so that the orthostatic column can respond to rapid changes in body orientation relative to gravity. Thus, baroreceptors can be said to function as accessory graviceptors.

Additional Findings

There are two additional findings that support an "extra-vestibular" input into spatial orientation. We have observed that on board ships individuals may entrain their breathing to the motion of the ship. In preliminary studies performed in our lab individuals on a ship were examined within 24 hours of departure of the ship. Those individuals who were experiencing motion intolerance displayed shallow, rapid breathing. At the 72-hour mark these individuals were re-examined and, in those who were no longer experiencing motion intolerance, their breathing was in phase with the ships roll frequency. Those individuals that continued to have motion intolerance continued to breath out of phase with the ships roll frequency. The influence of respiratory control on motion sensitivity cannot be explained by traditional balance theory.

Finally, we have demonstrated that a significant portion of individuals with clinical vestibular disorders respond to physical conditioning (exercise) alone with resolution of symptoms. Other than a small amount of strengthening of the legs, this exercise does not impact elements of the "traditional balance system". However, this cardiovascular conditioning does alter blood flow and cardiovascular performance. We feel that this cardiovascular improvement effects a portion of the bodies "extra vestibular" inputs and allows for the improvement in balance function noted in these patients.

An "Extra-vestibular" Input into Balance and Spatial Orientation

Based on the preliminary findings and to explain some of the ambiguities that occur when only the traditional vestibular theory is applied to some situations in motion environments, our group has proposed that the body uses a set of "extra-vestibular" inputs in spatial orientation. We believe that the body utilizes information gained from respiration, body posture, and the distribution of blood flow to help determine at least the position of the trunk in space. It is possible that a portion of the body's 'gravitoinertial framework map' is based on the experience of receptors associated with the hollow viscera of the abdomen and to the diaphragm and present inside blood vessels. Since childhood, the body learns that certain positional changes or certain postures exhibit a different set of influences on these extra-vestibular receptors. The gravitoinertial framework map may be based in part on the influences of extrinsic linear acceleration (including gravity) on movements of the small and large bowel, on dynamic movements of the ligament-tethered complex of the diaphragm, liver and stomach and on the distribution of blood in the vasculature. During quiet respiration in a static gravitointertial frame, the actions of gravity are unambiguous. However, in a moving frame, such as oscillations of a ship near respiratory frequency, the sum of the extrinsic motion and the self-generated respiratory movements may produce ambiguous information from abdominal and thoracic receptors if the motions are not in an appropriate phase relationship. Motion sickness, then, would simply a referred gastrointestinal distress from these ambiguous (conflict) situations.[4]

This modified sensory conflict framework may be applied to other situations in the same way as traditional sensory conflict theory. For example, the pilot "pulling G's" for the first time experiences a whole set of influences on the "extra-vestibular system" that may be in conflict with the traditional vestibular system. Over time a new extra-vestibular flying map is formed for this situation and as the pilot flies more the amount of spatial disorientation decreases. Once that pilot is placed in a flight simulator where the extra-vestibular signals are not the same as those in flight, a mismatch is created between the perceived vestibular and extra-vestibular information and this mismatch results in simulator sickness. Similarly, on board ships or in other operational environments, motion sickness or spatial disorientation can result when "extra-vestibular" information confounds or contradicts vestibular, visual and proprioceptive information. However, this conflict may be resolved by simple behavioral adaptations, such as entraining respiration with movement of a ship. This phenomenon may parallel the phenomenon of 'getting one's sea legs', whereby the motions of the ship become a baseline, stable framework for locomotion. Those who lack the appropriate adaptive learning capabilities (or who choose poor 'adaptive' strategies) will therefore not resolve the conflict and will suffer from motion sickness just as our patients have displayed.

The significance and exact mechanism whereby the "extra-vestibular" apparatus effect balance function demands further study. A research project is underway in our labs to more fully characterize the function of "extra-vestibular" inputs in determining spatial orientation. At the current time our theory is based on preliminary data and observed phenomenon, it must be backed up by solid science.

Implication of "Extra-Vestibular" Input into Spatial Orientation

The presence of "extra-vestibular" inputs into the balance system has significant implications especially to a military environment. The presence of these inputs presents a new set of targets for strategies to reduce motion intolerance and perhaps even increase (produce "super normal") spatial perception. The possible significance of "extra-vestibular" inputs into balance suggests that certain ergonomic design changes in military vehicles could minimize "neural map" mismatch or that training in an actual replica of an operational device might begin the process of formation of a new "extra-vestibular" map which would not be in conflict with the traditional vestibular system when the vehicle was truly being utilized. In addition, the presence of "extra-vestibular inputs" further supports the work of CAPT Rupert, as it is possible that the "balance suit" at least partially relies on "extra-vestibular" stimulation to "inform" the body of its spatial orientation.

Conclusion

Traditional teaching holds that balance function is based on three sets of inputs visual, vestibular, and proprioceptive. Work by our group, a consortium composed of members of the United States Military and investigators from the University of Pittsburgh, has begun to demonstrate that additional inputs may play a role in spatial orientation. These "extra-vestibular" inputs come from respiration, posture, and blood flow distribution and may play an important role in spatial orientation especially in motion environments. Our group is actively involved in basic research to determine the presence and significance of these "extra-vestibular" inputs. The presence of these inputs might provide a unique target for the treatment of vestibular disorders, the prevention of motion intolerance, and, even, the augmentation of spatial orientation in operational and non-operational settings.

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